xEMU Thermal Vacuum Testing Overview

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The Exploration Extravehicular Mobility Unit (xEMU) project was the culmination of over a decade of spacesuit development that was performed in-house at the NASA Johnson Space Center. This project reached a level where almost fully completed development fidelity spacesuits had been designed, assembled, and tested in an integrated configuration. The xEMU Design-Verification-Test (DVT) hardware was assembled into two different xEMU test articles and underwent a series of thermal-vacuum tests at the Johnson Space Center's Chamber B. These tests not only gathered data on thermal performance, but also exercised the life support system, communication system, suit information systems, and suit avionics. This complex test has and will continue to produce many meaningful reports ranging from component level test results (for example on spacesuit boots), test design of heater cages to simulate thermal environments for a spacesuit test article, and higher level thermal performance of subsystems (such as the Portable Life Support System) or the entire assembly. This paper provides an overview of the test configuration and also top-level results from this highly successful integrated test of the xEMU.

I. Introduction

THE Exploration Extravehicular Mobility Unit (xEMU) project brought over a decade of internal government spacesuit development to a climax. Technologies and architectures that were initially selected in the mid-2000's have undergone component and subsystem level development to enable fully integrated spacesuit level tests. The xEMU project performed a test series from 2021 to 2023 named Design-Verification-Test (DVT) which was envisioned as a dry run of qualification testing using the final set of hardware built prior to producing flight hardware fidelity systems. This DVT series included tests at the Exploration Portable Life Support Subsystem (xPLSS), Exploration Pressure Garment Subsystem (xPGS), and Exploration Informatics Subsystem (xINFO) levels prior to integration. The full xEMU was assembled for the first time in the summer of 2022, and a series of laboratory tests was performed at ambient pressures. Some upgrades to the xPLSS were needed following that test series and the xEMU test article was reassembled as a Short xEMU (SxEMU) after these changes were made. By the summer of 2023 another series of lab ambient tests was performed with this SxEMU to demonstrate that it was ready for thermal-vacuum testing which was conducted in the fall.

This paper provides an overview of these xEMU thermal-vacuum tests. Two xEMU test articles were used. The SxEMU, pictured in Figure 2, used this SxEMU configuration which included a full xPLSS, aluminum Hard Upper Torso (HUT), helmet assembly, xINFO lighting band and camera, and test equipment to simulate human metabolic products. A second test article, Suit 2, which is pictured in Figure 1, did not have an xPLSS but instead included a full xPGS to better capture the total heat exchange between the suit and the environment. Many additional papers, references 1 through 11, provide lower level details of specific aspects of xEMU performance. These include details on boot thermal performance, audio subsystem performance, or heat rejection performance. This paper provides an

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overview of the test and test articles to give additional context for these more detailed papers and to present a top level assessment of the xEMU performance in this high fidelity space-like testing environment.

II. Test Objectives

The primary objective of this test series was to test xEMU hardware in a high-fidelity simulated space environment. This included both space-like vacuum and a wide range of temperature extremes that were expected for either Extra-Vehicular Activities (EVAs) at the International Space Station or on the surface of the Moon. Objectives can be grouped into three categories. The first set of objectives focused on simulating EVAs with the hardware exposed to a wide range of thermal environments. Next, running the xEMU in vacuum conditions enabled sub-ambient pressure operation of the suit and its internal hardware. Finally, operating at the integrated spacesuit assembly level was an excellent opportunity to demonstrate the design and functionality of the xEMU.

Figure 2. SxEMU Test Article.

The xEMU had thermal environment requirements that ranged from 93K (-292°F) for a cold location on the lunar South Pole to 378K (+220°F) for a hot lunar crater. The vacuum chamber, Chamber B at the Johnson Space Center, used liquid nitrogen cooled cold walls to provide cold environments. It was understood prior to the test that the 93K test point could not be achieved in the facility and the test would simply get the minimum temperature that the chamber could provide. Heater cages were constructed around the two spacesuits to simulate the hot environments[3]. ISS thermal environments fell within that very extreme range of lunar temperatures.

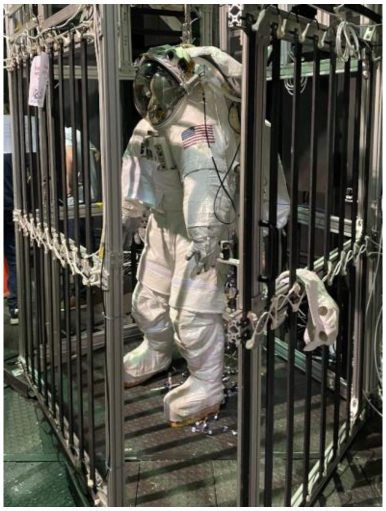

Figure 1. Suit 2 Test Article.

Figure 3. Suit 2 Thermal Image.

Figure 3 shows an infrared image of Suit 2 during testing. This test series consisted of mapping the performance of the xEMU across as wide of a temperature range as possible. This included mapping performance of the life support system components in different thermal environments, evaluating consumables usage, abort capabilities with the Auxiliary Thermal Control Loop (ATCL) and Secondary Oxygen Assembly (SOA), demonstrating Caution and Warning System (CWS) operation, and demonstrating the xINFO system (lights, camera, and telemetry transmission over Wi-Fi). Performing these simulated EVAs also enabled verification of numerous thermal models and performance of the Environmental Protection Garment (EPG). Heat transfer from the suit to the environment was estimated for different thermal environments and internal suit temperatures were checked against safe touch temperature limits for crew. The Suit 2 boots were in contact with the floor of the chamber, which was also cooled with liquid nitrogen and provided a unique and challenging boot thermal test.

Operating the xEMU inside the vacuum chamber enabled evaluating suit performance at sub-ambient pressures. Most spacesuit tests are performed in lab ambient conditions with the suit pressurized positively above 14.7 psia (101.3 kPa). This test put the xPGS components in vacuum conditions and then allowed for internal suit pressures around 4.3 psia (29.6 kPa) nominally. Running sub-ambient pressures allowed demonstration of both xPLSS oxygen regulators to operate at sub-ambient operating pressures. Also, it demonstrated pressure control across the xPLSS, xPGS HUT, and xPGS hatch through a wide range of pressure transients as the xEMU hardware was operated through different chamber pressure changes. Sub-ambient suit pressures were also a high fidelity test environment for testing

the xEMU integrated communication system. Performance of speakers and microphones are dependent on the density of the gas carrying the sound waves within the suit. Audio processing, including acoustic echo cancellation, also benefitted from testing at sub-ambient pressures. Finally, running the suit at vacuum conditions enabled different states and controls within the avionics that could not be exercised during lab environment tests. These include inhibits for turning off the oxygen regulators when the ambient pressure is at vacuum.

Testing at a high level of spacesuit integration was an excellent opportunity to evaluate the integrated performance of a complex system. Numerous component and sub-system tests were performed as part of the xEMU project utilizing hardware of various levels of fidelity and complexity. The SxEMU test article used for this thermal-vacuum test had the highest level of physical, electrical, and software integration of any xEMU test article used in DVT testing. For example, many life support components are located within the xPGS HUT and hatch and were only simulated during xPLSS level tests, whereas for this test series, the hardware was part of the SxEMU assembly. Successful assembly and checkout of the integrated SxEMU test article prior to thermal-vacuum testing was a significant accomplishment. The thermal-vacuum test setup also included high fidelity prototype vehicle interfaces including the Exploration Service and Cooling Umbilical (ESCU), a Fluid Pumping Unit Interface Requirements Demonstrator (FPU-IRD) for water recharge, and the Exploration Battery Management System (xBMS) for battery recharge. This was the highest fidelity and most flight-like test of the xEMU, including a high fidelity operational concept with airlock operations.

III. Test Configuration

Two xEMU test articles were tested in Chamber B at the Johnson Space Center (JSC). This chamber is the second largest thermal-vacuum chamber at JSC and is certified for manned spacesuit testing. However, due to the development fidelity of the xEMU hardware, testing was performed in an unmanned configuration. Gaseous nitrogen was used as the SxEMU pressure source instead of oxygen to reduce the risk of fire. Suit 2 used air as the pressurization gas.

Both xEMUs were located in Chamber B inside of heater cages, as seen in Figure 4. A large mylar curtain was placed in between the two suits to minimize thermal interactions between the two test articles. The SxEMU is on the left and the Suit 2 test article is on the right.

Figure 4. xEMUs in Chamber B.

Figure 5 provides an overview of how these two spacesuits were set up in the chamber and the test support equipment needed to test each of them. Suit 2 was located inside the main portion of the chamber and was at EVA conditions for the duration of the test series, which was approximately a week. It had test interfaces for audio equipment, power and data, suit ventilation, and two water loops to set temperatures in key portions of the test article that would represent thermal boundaries of the suit during a real EVA. The SxEMU passed between the

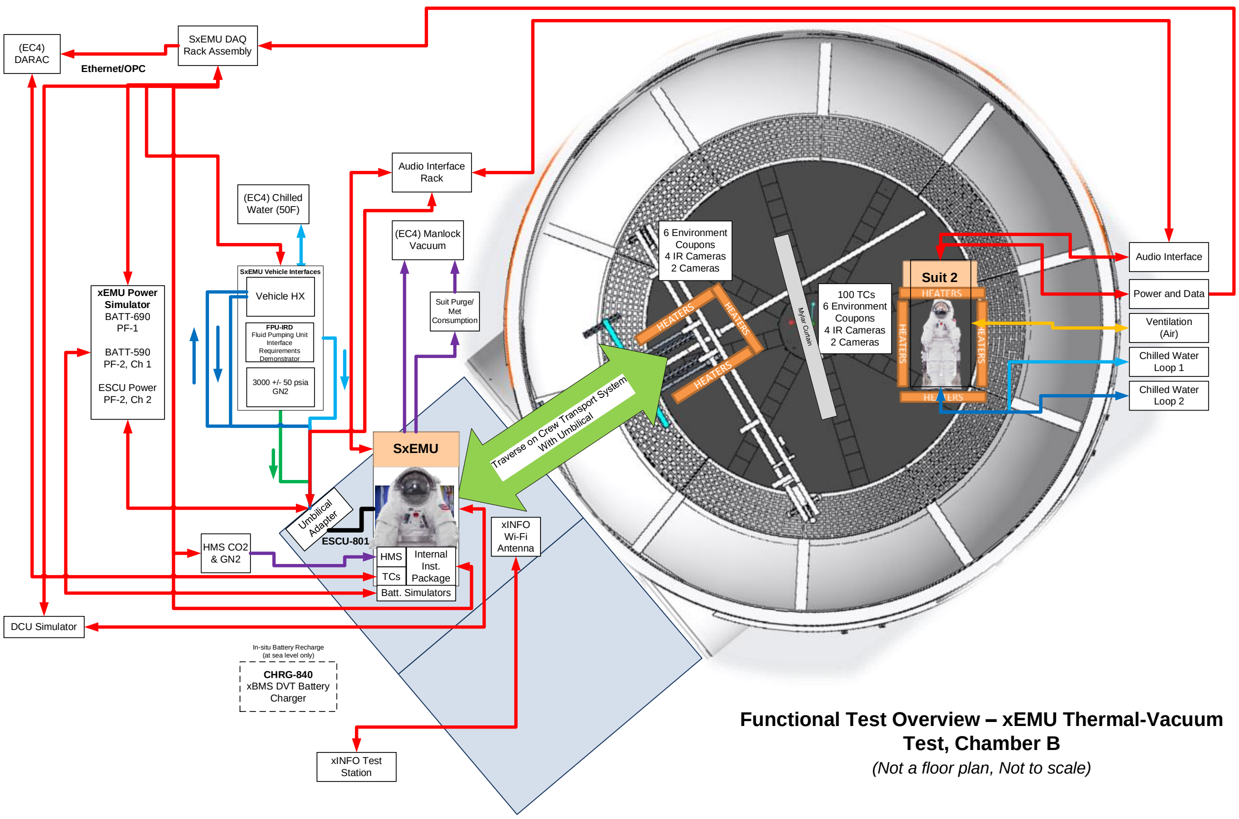

Figure 5. Test Layout.

Chamber B manlock and main portion of the chamber to perform discrete EVAs. Depressurizing the manlock, sending the SxEMU into the main chamber at vacuum and thermal conditions, returning to the manlock as suit consumables were expended, and repressurizing the manlock for suit recharge provided a very high fidelity operational concept for the SxEMU test points. In addition to these simulated vehicle interfaces, test equipment for the SxEMU provided simulated human metabolic input, a Wi-Fi interface for the xINFO, audio test interfaces, and test instrumentation. The following sections provide more details about these test configurations for both test articles.

A. SxEMU

Figure 6 shows the SxEMU traversing between the chamber manlock and the main vacuum chamber. Chamber B has a crew transport system that has previously been used to help crew members wearing heavy spacesuits to travel in and out of the chamber. For this test, the same overhead rail system and chain drive were used, but the test article support stand, and test umbilical were modified to support this unmanned test. The test umbilical provided power, data, and gas supplies to a human metabolic simulator (HMS) located under the SxEMU test article and also to an internal instrumentation package inside of the SxEMU test article. The HMS consisted of flow controllers for CO2 and water, an evaporator, and flow controllers to pull gas from the SxEMU to simulate oxygen consumption by a crew member or simulated suit purge valve operation. Inside of the HUT, the internal instrumentation included an audio manikin, three measurement microphones, two accelerometers, and a set of instrumentation to monitor xPLSS performance. Figure 7 shows how the data collection system, CO2 sensor, NH3 sensor, humidity sensors, pressure sensors, flow sensors, and temperature sensors were packaged to fit inside of the SxEMU. This internal instrumentation package closed the Primary Thermal Control Loop (PTCL) and ATCL where

Figure 6. SxEMU Translation.

a Liquid Cooling and Ventilation Garment (LCVG) would normally be placed. Fluid, power, and data connections for internal instrumentation were routed out of the suit through a custom waist close out plug, shown in Figure 8, and then routed through the test umbilical to test support equipment outside of the chamber. CO2 and humidity from the HMS were injected into the HUT through this waist plug and then routed to the crew right arm through internal tubing. A real xEMU ventilation tree was used inside of the SxEMU with the lines that would normally go to the legs of the suit routed to the arms instead. Coldplates with electrical heaters were part of the HMS under the SxEMU and injected heat into the thermal control loops of the suit in place of heat produced by a crew member wearing an LCVG. 32 thermocouples were placed at key locations on the inside of the SxEMU and routed through the internal instrumentation package. 96 additional thermocouples were placed on the outer portions of the SxEMU.

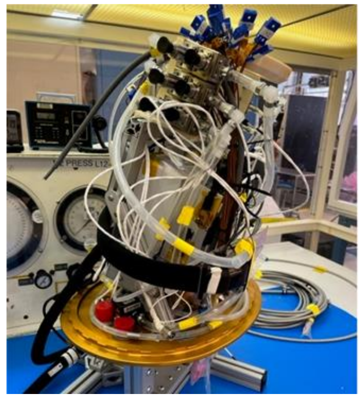

Figure 7. Internal Instrumentation Package.

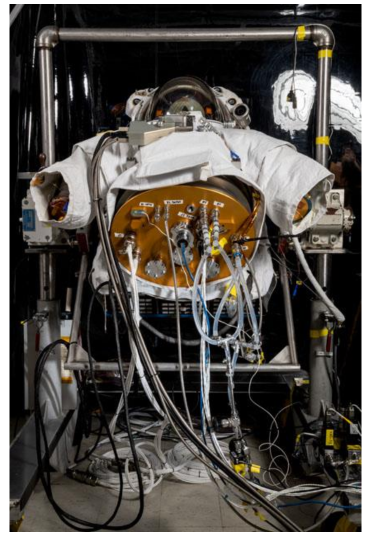

Figure 8. SxEMU Waist Plug.

The SxEMU itself was an almost complete xEMU. It was missing the waist brief, lower torso, and boots. The LCVG was replaced with the internal instrumentation, the Wired Heart Rate Monitor was not used, and there were not any gloves. The xPLSS was missing the Active Radiation Dosimeter and the radio was terminated with 50 Ohm resistive loads but was otherwise consistent with the xEMU design.

Figure 9. Suit 2.

B. Suit 2

Suit 2 provided a full xPGS test article and an improved opportunity to assess the full suit heat exchange with environments of different temperatures. Figure 9 shows Suit 2 in a partially assembled state. It included a weight relief plate, where the xPLSS would normally be installed, to suspend the xEMU from an overhead I-beam inside of the chamber. Inside of the suit was a manikin wearing an LCVG. This provided a high fidelity thermal boundary on the inside of the suit to assess the heat transfer through the suit to the environment. Modifications were made to the LCVG to better represent a crew member’s hands and feet. These are shown in Figure 10. Normally the LCVG does not cover hands and feet, but in order to provide some thermal interface inside of the gloves and boots of the suit, extra tubing was added to the fluid loop and sewn into comfort gloves and around socks to simulate the temperature of a crew members hands and feet.

Figure 10. Suit 2 LCVG Modifications.

The Wired Heart Rate Monitor was not included in Suit 2, a high fidelity lighting band was included, and the camera was simulated thermally by placing a properly sized resistor inside of a spare camera body to produce a representative amount of electrically produced heat. The Display and Control Unit (DCU) was a stand in unit with a body constructed from Ultem instead of aluminum. This was previously explored as a mass savings idea but was not chosen due to thermal concerns discovered via modeling. Since there were two DCUs in this test (one on Suit 2 and one on the SxEMU), one of each base material was used and compared back to those previous analyses. The Liquid Crystal Display (LCD) and internal electronics on the Suit 2 DCU were high fidelity and identical to the one on the SxEMU. A test box was designed to send different messages across the display throughout

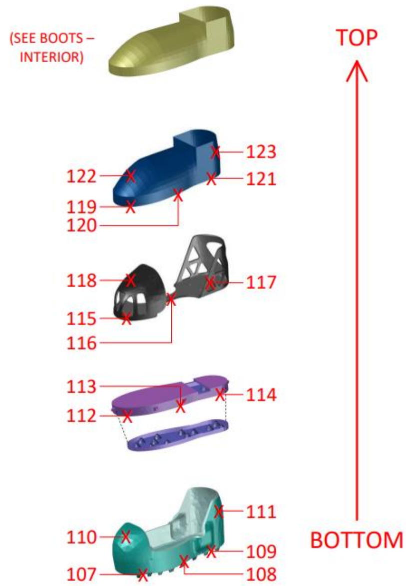

Figure 11. Thermocouple Layout for Suit 2 Boot.

the test and the pan-tilt-zoom video cameras inside of Chamber B enabled observing the LCD on both suits at different temperature extremes. A lower fidelity Service and Cooling Connection (SCC) was used in the Suit 2 DCU. It was made of stainless steel and provided ports to attach fittings and a small piece of tubing to close the PTCL at the DCU, as opposed to the quick disconnects and electrical connector needed for a real suit application. This was an important aspect of the DCU because the water lines flowing through provided a boundary temperature for the heat transfer through the component and also to the environment.

Test support equipment was needed for Suit 2 in order to collect data and also to simulate the appropriate conditions inside of the suit for the test. Like the SxEMU, it also had an internal instrumentation package that consisted of a data collection system that monitored temperatures in two independent water loops that flowed inside of the suit, temperatures in the ventilation gas that circulated through the suit, audio equipment, and 48 internal thermocouples. 121 thermocouples were placed outside of the pressurized portion of the suit and care was taken to try and capture temperature changes through the multi-layered layup of the suit to evaluate thermal performance. Figure 11 is an example of this multi-layer approach as was applied to one of the boots[9]. Internal audio equipment consisted of the xEMU Integrated Communication System (ICS) speakers and microphones, an audio manikin, and a single measurement microphone. To pressurize the suit and simulate a 6 acfm (170 ALPM) flow rate, a ventilation cart was built and placed outside of the chamber. The cart contained two small scroll vacuum pumps that pulled air from the building through a test umbilical to the suit and then back out. A flow controller and metering valve were used to set the target flow rate and suit pressure, which was 4.3 psia (29.6 kPa).

Two independently controlled fluid thermal loops were used to set temperatures within Suit 2. Each was a pumped water loop with a chiller that also had some heating capability and could control to a set temperature. One water loop simulated the crew inside of the suit. This loop was set between 75 and 85°F (24 – 29°C) to simulate the thermal condition a crew member wearing an LCVG would generate inside of the suit. Temperature and flow direction were varied during the test matrix as the thermal environments transitioned from cold to hot. The second water loop was set to 50°F (10°C) and simulated the xPLSS. The xPLSS controls to a 50°F (10°C) outlet temperature at the Suit Water Membrane Evaporator (SWME) and this becomes a key temperature boundary for the xEMU in several locations. First, the xPLSS itself is a temperature boundary to the back portion of the xEMU HUT. Therefore, this 50°F, or xPLSS, water loop was pumped through coldplate heat exchangers that were attached to the weight relief plate on the back of Suit 2 (shown in Figure 9). In addition, the xPLSS loop flowed through water lines that were located inside of the HUT to connect the xPLSS to the DCU. The 50°F (10°C) water provided some thermal boundary inside of the HUT through this line and it set the temperature of the DCU.

C. Audio

This xEMU thermal-vacuum test provided an opportunity for possibly the highest fidelity spacesuit audio test ever performed. It contained two suits, both at sub-ambient pressures, that could talk to each other. Both suits had high fidelity ICS speakers and microphones, ventilation ducts, and proper gas flow. SxEMU also included the xPLSS, which has been determined to be a significant noise source due to fan and pump operations. Unfortunately, the communication performance of the xEMU radio was not refined enough at this point in time to use as part of the test, so the radio functionality was incorporated into the test setup.

The audio test system design spanned both suits and is shown in Figure 12. Both suits used test boxes immediately outside of the chamber to interface with the ICS speakers and microphones. These are labeled 701 and AEC Dev Board in Figure 12 (green boxes). They also incorporated the Acoustic Echo Cancellation (AEC) algorithm and processing needed to pull the in-bound communication signals (coming from the speakers) from being sent back out of the outbound signals (going through the microphones). These test boxes connected to an audio test system that consisted of multiple computers, mixing and recording software, and racks full of signal processing hardware. Multi-track recordings were made during testing that were later analyzed to better evaluate the acoustic performance of the xEMU. Both suits used the head portion of a Bruel & Kjaer head and torso simulator. These audio manikins had a

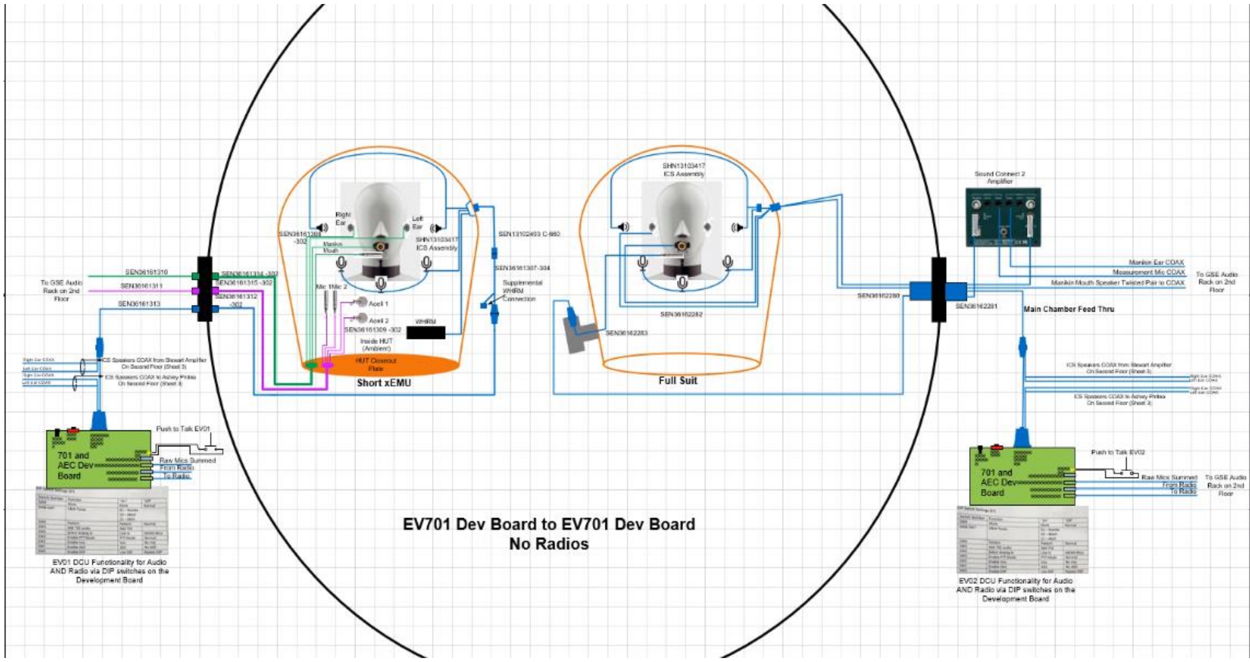

Figure 12. Audio Test Setup.

speaker located in the mouth that could speak and microphones in the ears that could listen. Two accelerometers were used inside of the SxEMU to provide insight into vibrations that might be related to structural borne noises in the suit. Additional description and results on the audio testing can be found in Reference 11.

IV. Results Summary

Thermal-vacuum testing was performed from September 28th through October 3rd, 2023. Once the chamber was pumped down, all testing operations proceeded smoothly. Separate test points were performed between the two test articles during the week of around-the-clock test operations. In general, it took approximately a day for the chamber to get cold once at vacuum. From that point forward, test points on both suits were organized so that the cold thermal environments were tested first and then the heater cages were used to increase the radiation environment temperatures at testing progressed with the suits experiencing the hottest environments at the end of testing. The following section summarizes the top level results, with several additional papers (References 1 through 11) exploring more details of the performance of the xEMUs.

A. SxEMU

The SxEMU performed 5 EVAs throughout the week of testing. These began with simulated airlock operations in the chamber manlock. During this period the xPLSS oxygen tanks, water bladders, and batteries were all charged. Gaseous nitrogen was used to pressurize the suit in this test instead of oxygen. The ESCU was demated from the DCU and the suit was prepared to perform an EVA. After the manlock was depressed, the crew transport system would transfer the SxEMU into the heater cage inside of the chamber. Heaters were pre-set to specified environment conditions prior to each EVA. A simulated EVA was performed with specific test objectives while the SxEMU consumables were monitored. Once the test team determined each EVA was completed, the crew transport system returned the SxEMU to the manlock, the manlock was repressurized and the team was allowed to re-enter and then recharge the system in preparation for the following test. Table 1 summarizes the 5 EVAs and different test points performed for each.

EVA duration is typically measured from the time that a spacesuit transitions from hardline power to batteries. Normally this is one of the steps a crew member completes before demating the umbilical and going “out the door.” For this unmanned test, the umbilical had to be demated prior to pumping down the manlock and ended up being performed towards the beginning of the simulated airlock operations. Test personnel had no physical access to the

Table 1. SxEMU Test Points.

Test Point	1	2	3	4	5
EVA Duration - BATT (hr)	13.7	11.8	11.1	12.6	8.8
Time at Vacuum (hr)	8.8	10.6	9.1	11.4	6.3
GN2 Used (lbm)	0.70	1.76	1.81	1.63	0.74
Water Used (lbm)	4.60	6.45	10.70	9.48	4.73
Metabolic Profile	RCA Mapping, SWME mapping	RCA mapping, SWME mapping	SWME mapping	RCA mapping, SWME mapping	4.3, 5.0, 6.2, and 8.2 psid ops
Environment	Cold	Cold	Hot	Hot	Hot
Visor/Shades	Shade Deployed	Stowed	Deployed	Stowed	Deployed
POR/SOR Inhibit		x			
POV Depletion		x	x	x	
POR Purge		x	x	x	
SOR Purge			x		
ATCL Operations	Airlock			Mapping	

SxEMU after the manlock door was closed and pump down had begun. Therefore, test point "EVA duration" and "Time at Vacuum" are both useful parameters to assess how long the EVA lasted.

Consumables were also tracked for each EVA. Battery capacity was never a limiting consumable with voltages not dropping below 25 VDC on any of the EVAs except the first one where there was an extended period of non-vacuum battery operations due to the test team working through the testing sequences for the first time. GN2 and water use was tracked for each EVA also. It should be noted that nitrogen is less dense than oxygen so those usage numbers may appear slightly lower than expected for a normal EVA. EVAs 2 through 4 all included fully depleting the primary oxygen tank and watching the Secondary Oxygen Assembly (SOA) automatically take control of pressurizing the suit.

Additional test objectives for each EVA include metabolic performance assessments, thermal environment, helmet assembly configuration, Primary Oxygen Vessel (POV) depletion, Primary Oxygen Regulator (POR) purge testing, Secondary Oxygen Regulator (SOR) purge testing, and ATCL operations.

The xPLSS Rapid Cycle Amine (RCA) swing bed CO2 scrubber demonstrated poor performance during the first EVA and the planned metabolic profiles were abandoned. The half-cycle time of the beds approached the 15 second minimum duration at metabolic rates in the 1200 BTU/hr range which was unexpected and made continuing metabolic profiles with rates up to 3000 BTU/hr an undesired test activity. More discussion on the RCA performance is included in the following Issues and Anomalies section. From that point forward, performance mapping activities were used as test points for the RCA and the SWME. Test points were set up where the CO2 injection rate or heat input rate were stepped up methodically and the system could be monitored for steady state performance.

EVAs 1 and 2 were performed in cold thermal environments with EVAs 3, 4, and 5 in hot environments. Some precautions were made with the SxEMU test article with respect to thermal environments because this was an unmanned test. Because there was not a crew member or an LCVG inside the xPGS portion of the test article, it was unknown how closely the xPGS components would track with the external thermal environments. The crew member and LCVG provide a significant thermal mass and temperature sink in a real EVA scenario. Therefore, the SxEMU was divided into two different thermal zones and the xPGS was controlled to more neutral environments than the xPLSS. References 1 and 3 provide additional details. After some experimental trial and error, the outer xPGS EPG layer (which approximated the environment temperature) hit low temperatures of 40°F (278 K) and a high temperature

of 180°F (355 K). The xPLSS EPG got as cold as -108°F (195 K) during cold environment testing and up to 230°F (383 K) during hot test points. The sun visor and shade positions were typically alternated in between test points so that their impact on the overall system heat transfer could be assessed in hot and cold environments.

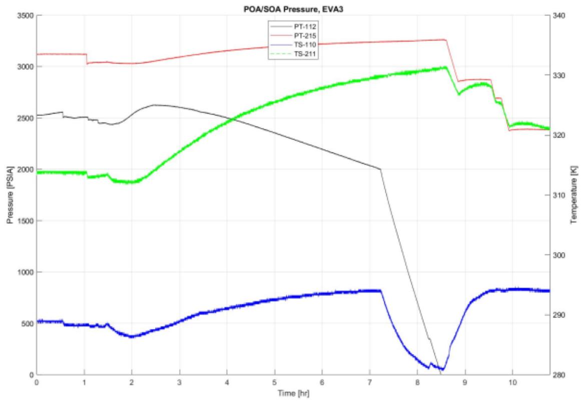

Figure 13. EVA 3 POA/SOA Performance

EVAs 2, 3, and 4 all had periods where the simulated purge valve was opened, and the POR tried to maintain the suit pressure as the primary oxygen tank was depleted. These tests provide data on regulator performance vs. flow rate, provide interesting thermal data as the tanks cool off due to the gas expansion during high flow operations, and enabled demonstration of the SOR taking control of maintaining the suit pressure as the primary system finally ran out of gas. Figure 13 shows the POA and SOA pressures and temperatures during a test where both regulators experienced purge flow operations. Shortly after EVA hour 7, the simulated purge valve was opened, and the tank pressure (PT-112) and tank temperature (TS-110) decrease rapidly. As PT-112 approaches 0 psia (0 kPa) at EVA hour 8.5, the secondary tank begins to respond. PT-215 (secondary tank pressure) and TS-211 (secondary tank temperature) both start to decrease rapidly as the SOR continues to feed the purge valve based flow rate. The SOA was never fully drained during testing to ensure that there was enough gas to repressurize the suit after each EVA when the manlock was repressurized. This repress can be seen as the two-step decrease in tank pressure (PT-215) at EVA time of approximately 9.5 hours.

Smaller one-time tests were also spread across this set of simulated EVAs. RCA CO2 scrubber operations were tested during airlock operations using an upgraded facility manlock vacuum system during EVA 1. Regulator inhibits were tested during EVA 2 to demonstrate that the system prohibits a crew member from turning off either of the oxygen regulators while the suit is at vacuum conditions. Performance of the ATCL was functionally checked at the beginning of EVA 1 and then mapped during EVA 4. The POR was used to operate at all of the available suit pressures during EVA 5. This included 4.3 psid (30 kPa), 5.0 psia, 6.2 psia, and 8.2 psia.

Table 2. Suit 2 Test Points.

Number	Profile Name	xINFO	Floor LN2	Duration
1	Chamber Cooling	On	On	4 Hr 40 Min
2	Cold	On	On	14 Hr 25 Min
3	Cold (Warming Front of Suit)	On	On	5 Hr 38 Min
4	Cold (Warming Front of Suit)	Off	On	5 Hr 52 Min
5	Max Cold	On	On	11 Hr 46 Min
6	Max Cold	Off	On	8 Hr 20 Min
7	Heating Top Half	On	On	14 Hr 25 Min
8	Heating Front	Off	Off	11 Hr 56 Min
9	Max Hot (Bubble 220F)	On	Off	9 Hr 45 Min
10	Max Hot (Even 200F)	On	Off	9 Hr 36 Min
11	Chamber Warming/Repress	Off	Off	12 Hr 16 Min

B. Suit 2

Suit 2 performed a single EVA that lasted 116 hours. It went to EVA conditions as soon as the main chamber was pumped down, cooled down along with the chamber for approximately a day, went through 11 test points that utilized a variety of heater cage settings, and then repressed with the chamber at the end of the week. Table 2 outlines these test points, including test duration. Test points were held until thermal analysts could determine that the suit had

reached close to a steady state temperature. In some cases, this meant holding at test condition for much longer than what a person could have comfortably done inside of a suit. Several of these test points exceeded a nominal 8 hour

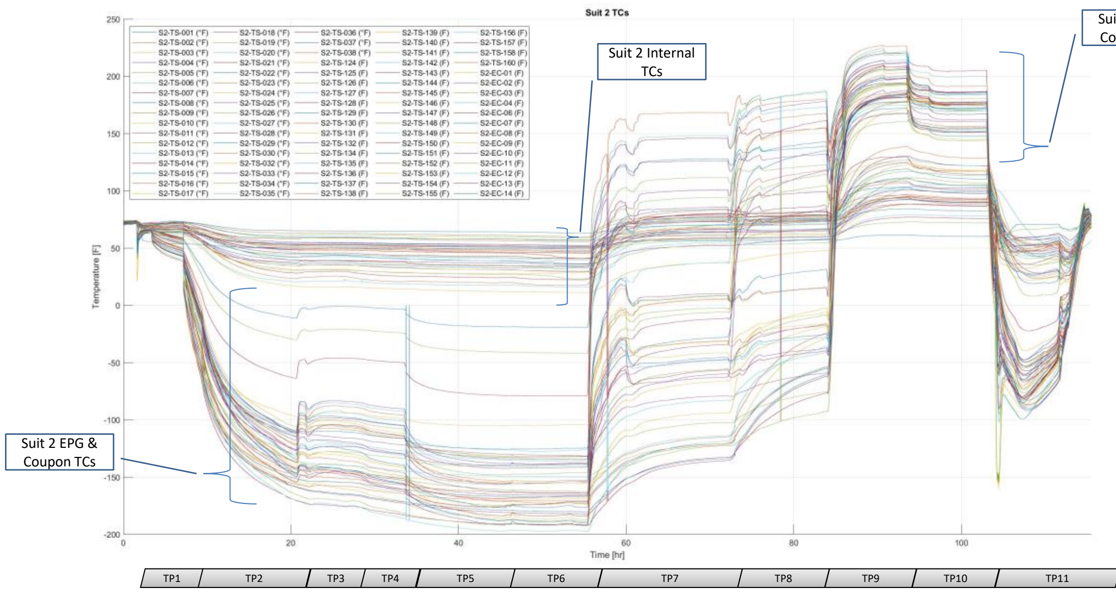

Figure 14. Suit 2 Test Point Summary

EVA duration. Test points started with cold environments and then progressed warmer by increasing heater power settings and eventually turning off the liquid nitrogen flow to the floor underneath the suit. The xINFO lighting band and camera simulator were turned on and off for different test points to assess the impact of their heat generation at the top of the suit. Floor temperatures under the boots ranged from -250°F (116 K) to 165°F (347 K) from the coldest to hottest test cases. General suit temperatures on the outside of the EPG ranged from -190°F (150 K) to 230°F (383 K) during testing. Figure 14 shows Suit 2 temperature throughout the entire test profile. The test points (TP) are noted on the bar at the bottom. There are likely too many thermocouples represented to pull out specific data, but the groupings show that the EPG worked well across the range of environments. Through the first 6 test points the EPG and environment coupon temperatures indicated very cold values, but the internal thermocouples remained between approximately 30°F (272 K) to 70°F (294 K). Similarly in the hottest cases, TP 9 and later, the EPG and environment coupons were quite hot but most of the internal thermocouples still read between 50°F (283 K) and 100°F (311 K). Additional detailed analysis is performed in more focused reports on specific locations or components of the xEMU.

C. Issues and Anomalies

Overall, the xEMU hardware worked extremely well. This was the highest fidelity test performed through the whole history of NASA's current spacesuit development effort. Some items did not perform as expected and are notable. These may be good areas of future technology development, indicate risks with future spacesuit development, or be short comings in the xEMU design.

The LCD used in both DCUs did not perform well during cold temperatures. This was not a surprise due to previous performance of LCDs in similar environments. As the temperatures got colder, the display updated more and more slowly. Once cold enough, the characters were no longer visible. However, once the hardware warmed up again, it appeared to work properly.

An issue was experienced when recharging the oxygen tanks in which gas (in this case nitrogen) would not flow into the tanks when the supply pressure was set to 3000 psia (20,680 kPa). Gas would flow if the pressure was gradually stepped up in smaller increments and the SxEMU tanks could be charged in between EVAs using this work around procedure. The issue was isolated to the ESCU or DCU where there are some complex and tightly toleranced assemblies that seal the oxygen recharge lines when demated but allow them to flow when mated. Additional investigation into this issue was underway at the writing of this paper.

The xINFO avionics box, EV-702, experienced several lock ups during testing. This was also not a surprise due to previous behavior in other tests and was always recoverable through a power cycle either through sending commands over the Wi-Fi interface or a power cycle through the DCU menus. No root cause has been identified at the time of this paper.

The xINFO camera also had intermittent issues where it shut off in hot thermal environments. This occurs from time to time with the ISS EMU high-definition camera that this design was based on and was expected. Once the unit began to overheat, it was shut off until it reached an acceptable operating temperature and then was restarted.

Several issues were present with the xEMU audio and communication system. As previously noted, the radio had not been matured to a level for it to be included as part of the communication system chain. Noise inside both suits was an issue, although the SxEMU with the xPLSS had more noise due to the fans and pumps in the life support system, which was a higher fidelity test case. One of the speakers in Suit 2 appeared to fail at some point during testing. Reference 11 addresses audio issues in more detail. This is an area where continued development is needed.

Humidity injection from the human metabolic simulator into the SxEMU test article did not work well. Water was evaporated and then flowed through the upper torso and into the right arm of the suit. Based on humidity sensor readings from the internal instrumentation package, it appeared that a high percentage of the water was condensing in the line before it got to the suit free volume. In addition to not wanting to collect a puddle of water inside of the suit, the arm bladder near the gas line exhaust began to heat up toward the temperature limit. At that point, humidity injection was stopped to reduce the risk of damaging the test article. Carbon dioxide injection was still used in subsequent RCA performance assessments.

The RCA performance showed significantly less capacity than expected. This issue had not been resolved at the writing of this paper and is forward work. The unit reached minimum half cycle times of 15 seconds (as controlled by the ventilation loop controller) at simulated metabolic rates of approximately 1200 BTU/hr. This is an average metabolic rate and significantly less than the 3000 BTU/hr maximum that the xPLSS should be able to support. Some trouble shooting was done during test operations to verify that injection rates and CO2 sensor readings seemed appropriate. Additional potential issues could be related to the lower humidity (due to the test issues with humidity injection), poor vacuum quality, or some aspect of the RCA itself. This unit had previously demonstrated poor performance and was refurbished prior to this test. Potential issues in the RCA itself could be channeling in the packed beds so that the ventilation gas does not flow uniformly across the amine or general degradation of the amine itself. A subsequent test is planned at JSC in a separate test facility where the humidity and vacuum pressures can be evaluated. The forward plan on this piece of hardware will be reassessed after those tests are completed. It should be noted that a different unit (SN 002) had been used for the past year and had shown good performance, so this issue it likely not a general issue with the technology.

ATCL operations demonstrated two minor issues. First, the ATCL switch on the DCU simultaneously turns on the pump that circulates water through the system and opens the backpressure control valve on the HX-540 Mini-SWME (or MiniME) to let water begin to evaporate and provide cooling. When the ATCL switch is turned off, the pump shuts down and then the valve is closed. The issue is that after the pump is shut down, the water in the MiniME becomes stagnant and continues to evaporate, rapidly cooling the membrane fiber bundle in the HX-540. A software change is recommended to change the order of actions when the switch is set to the off position so that the back pressure valve closes first, stopping water evaporation and cooling, and then the pump is shut off afterwards. In addition to this minor operational sequence issue, the actuator on the HX-540 back pressure valve may have experienced sticking during closing operations. The potentiometer on the valve did not always read fully closed when the valve was set to the closed position. The offset was small enough that additional evaluation is required. Linear actuators that drive the xPLSS valves and regulators have had a history of issues with sticking, although a lubricant modification in 2022 has dramatically improved performance so much that none of the actuators have required "unsticking" since the change was made. In this instance, the valve was cycled several times and returned to what should have been the fully closed position as measured by the potentiometer on the valve.

PT-112 is the pressure transducer that measures the pressure of the primary oxygen tank. It demonstrated spurious behavior during testing where it did not reach the same pressure as PT-215 on the secondary tank during charging, but once the ESCU was disconnected and the SxEMU reached vacuum conditions, the PT-112 reading rose by a few hundred psia. This can be seen in Figure 13 as the rise in PT-112 pressure shortly after hour 2 of the EVA. After reviewing tank charging data from the test system, which included additional pressure, temperature, and flow rate data, it was determined that this must be erroneous readings from that specific sensor. It will be removed from the xPLSS, recalibrated, and replaced.

Infrared cameras were used to monitor temperatures of both xEMU test articles during testing. These were unmodified commercial-off-the-shelf units that were relatively low cost. They worked very well during cold tests,

but all of the cameras eventually shut off due to over temperature conditions during the hot test points. Minimal effort was made to isolate the cameras thermally from the heater cages so they may have been exposed to very hot temperatures. They appeared to be a good instrument for use in future tests, but additional thought should be put into keeping them from getting overheated in hot test points.

V. Conclusion

Thermal-vacuum testing of the xEMU, through the SxEMU and Suit 2 test articles, was incredibly successful and provided an excellent demonstration of the design of this spacesuit that NASA has developed. Not only did this test series demonstrate the maturity and functionality of the xEMU, but it provided many data sets that can be studied as part of future spacesuit development efforts. Areas of needed improvement were identified that can serve as risks for future spacesuit vendors to navigate or future areas that would benefit from continued technology development. It provided the NASA team with valuable experience in the testing environment with respect to interfacing new spacesuits to legacy facilities that have primarily been testing the ISS EMU for over 40 years. This test was a successful capstone activity to this current generation of NASA spacesuit development.

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This work was funded by the EVA and Human Surface Mobility Program. It is the culmination of over a decade of work developing what has become the NASA government reference design for future spacesuits. Hundreds of dedicated people have worked on this spacesuit design over this period and are worthy of recognition for their hard work and expertise. Demonstrating this new spacesuit in a high fidelity space-like environment is a very significant accomplishment and could not have happened without their contributions over the years.

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